

## Energy Absorption Characteristics of Polyurethane Composite Foam-Filled Tubes Subjected to Quasi-Static Axial Loading

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**Keywords:** Energy absorption; foam-filled tubes; axial loading; polyurethane; foams; composites

**Abstract.** Foam-filled enclosures are very common in structural crashworthiness to increase energy absorption. However, very less research has been targeted on potential use of natural/recycled material reinforced foam-filled tubes. Therefore, an experimental investigation was performed to quantify energy absorption capacity of polyurethane (PU) composite foam-filled circular steel tubes under quasi-static axial loading. The thickness of the tubes was varied from 1.9, 2.9 and 3.6 mm. The tubes were filled with PU composite foam. The PU composite foam was processed with addition of kenaf plant fiber and recycled rubber particles that were refined at 80 mesh particulates into PU system. The density of PU resin was varied from 100, 200 and 300 kgm<sup>-3</sup>. The PU composite foam-filled tubes were crushed axially at constant speed in a universal testing machine and their energy absorption was characterized from the resulting load-deflection data. Results indicate that PU composite foam-filled tubes exhibited better energy absorption capacity than those PU foam-filled tubes and its respective empty tubes. Interaction effect between the tube and the foam and incorporation of filler into PU system led to an increase in mean crushing load compared to that of the unfilled PU foam or tube itself. Relatively, progressively collapse modes were observed for all tested tubes. Findings suggested that composite foam-filled tubes could be used as crashworthy member.

### Introduction

The protection of the structures is required to absorb impact energy during crushing events in a controlled manner and hence protect the structure under consideration [1,2]. From wide range of applications, automotive structure is one of most important component in vehicles due to its function to protect the passenger compartment. In general, vehicle structures are using steel tube or aluminum tube with different geometric structures to function as energy absorbers whilst paying more attention to the new concept about lessen fuel consumption and lower carbon dioxide (CO<sub>2</sub>) emission with weight consideration.

As a results, thin-walled tubes, particularly those of circular and square cross sections, are common type of energy absorbers since they are relatively cheap, versatile and efficient for energy absorbing [3-7]. In addition, polymeric foams are widely used in the automotive industry to prevent injuries to the occupant in the event of front or side collisions [8]. There is an increased interest in using these polymeric structural foams as fillers inside thin-walled metallic enclosures to function as energy absorbers because such combinations are very effective in energy absorption application, keeping the peak force below the limit that causes damage and injury in vehicle accidents [9-11].

Relatively, many investigations have been conducted on energy absorption performance of foam-filled tubes. Hanssen et al. [12] performed an axial crushing investigation to study optimum design for energy absorption of square aluminum columns with aluminum foam filler. They found a

significant increase in crushing force from the compressive strength of the foam and the interaction between the foam and the wall column. Feng et al. [13] studied the quasi-static axial compression of aluminum foam-filled square tubes. They identified the compressive load and energy absorption of foam-filled and empty tubes in transverse direction were lower than that in the longitudinal direction. This is due to the foam presence in longitudinal direction provides better interaction between the tube and the filler than that in transverse direction.

Salimi et al. [14] studied the crushing behavior of the empty and foam-filled thin-walled tubes under static and dynamic loadings. They emphasized the effect foam density on crushing behavior of rectangular tubes. Mantena et al. [15] analyzed the impact and dynamic response of three high density polymeric structural foams and used as filler inside circular steel tubes and found the lowest density foam ineffective as filler in their application. Further, they validated their crushing test results with finite element model analysis.

Thornton et al. [16] conducted comprehensive quasi-static and dynamic compression of polyurethane foam-filled thin-walled sections and found filling with polyurethane foam was not weight effective, unless relatively thin sections made of high density low strength alloy such as mild steel were used. Ismail et al. [17] studied crushing characteristics of polyurethane foam-filled columns that varied in thickness and found foam density plays insignificant roles when thick tubes were used. Onsalung et al. [18] further investigated the influence of foam density on specific energy absorption of rectangular tubes. They revealed tubes with higher density foam can absorb more energy absorption and found that optimum foam density of  $200 \text{ kg m}^{-3}$  provides maximum specific energy absorption. Khanna [19] studied application of chopped glass fiber strands reinforced polyurethane foam-filled tubes for improving energy absorption and found better properties than unreinforced foam-filled tubes.

However, relatively fewer investigations are reported on the crushing characteristics of composite foam-filled tubes. Therefore, an experimental investigation was performed to quantify energy absorption capacity of polyurethane (PU) composite foam-filled circular steel tubes under quasi-static axial loading. Crush characteristics included deformed shapes, peak force, energy absorbed and mean crushing force were presented and analyzed from resulted load-displacement data. The results of these data were compared with unfilled PU foam-filled tubes (PUF) and empty tubes (E).

## Experimental

**Materials.** A two-component polyurethane (PU) consisted of polyol and 2,4-diphenylmethane diisocyanate (MDI). Both components are liquid at room temperature. Kenaf bast fiber and recycled tire rubber particles were obtained from industries. The size of kenaf fibers and recycled tire rubber particles obtained was 80 mesh. Steel tubes used in this study were graded as BS1387.

**Processing method.** Tubes of 60 mm nominal diameter and varied thickness from 1.9 (T1), 2.9 (T2) and 3.6 mm (T3) were obtained commercially and later cut to make specimens of the required length. The tube length selected for the test condition is 200 mm. The tubes are filled with PU composite foam. The composite PU foams were prepared using the formulation described by Badri et al. [20] and three different PU resin densities were used such as 100, 200 and  $300 \text{ kg m}^{-3}$ . The incorporated filler into PU system was fixed at 6% weight percentages. Three different composite foam-filled tubes were produced using the methods such as kenaf fibers reinforced polyurethane foam-filled tube (KFPU), rubber particles reinforced polyurethane foam-filled tube (TRPU) and the combination of kenaf fibers (50 %) and rubber particles (50 %) reinforced polyurethane foam-filled tube (KRPUP).

**Test methods.** The quasi-static axial compression tests were carried out in a SHIMADZU 1000kN universal testing machine. The testing mode was displacement control with the top platen of the machine being moved vertically downward to compress the empty and foam-filled tube specimens that being placed on fixed bottom platen. The tube specimens were properly aligned to be eccentric with flat end platens to prevent bending moment occurs during crushing process. A series of 117 axial compression tests were conducted under quasi-static condition with three

repetitions of each samples. Tests were carried out with cross-head speed was approximately 5 mm/min. The specimen was unloaded and the experiment stopped when the tube collapsed until 60% of the original height.

### Results and discussions

In the quasi-static test, load and displacement were measured for all tested tubes, and the following response parameters were obtained based on these measurements such as the peak force, energy absorbed, mean force and the deformation mode.

**Load-displacement curves.** The load-displacement curves of the empty and foam-filled tubes are illustrated in Fig. 1a-1c and Fig.2. The resultant curves show an alternate high and low peak loads that characterize the crushing process of the tubes. These peaks correspond to the formation of the outward and inward parts of the lobes along the crushing tubes. Two principal modes of deformation was observed such as concertina and mixed mode. The number of lobes occurred along the deformation was observed varied for different tube thicknesses and decreases with increased tube thickness. Furthermore, filling of foam inside tubes offer better energy absorption performance but it roles become insignificant when larger tube thick used.

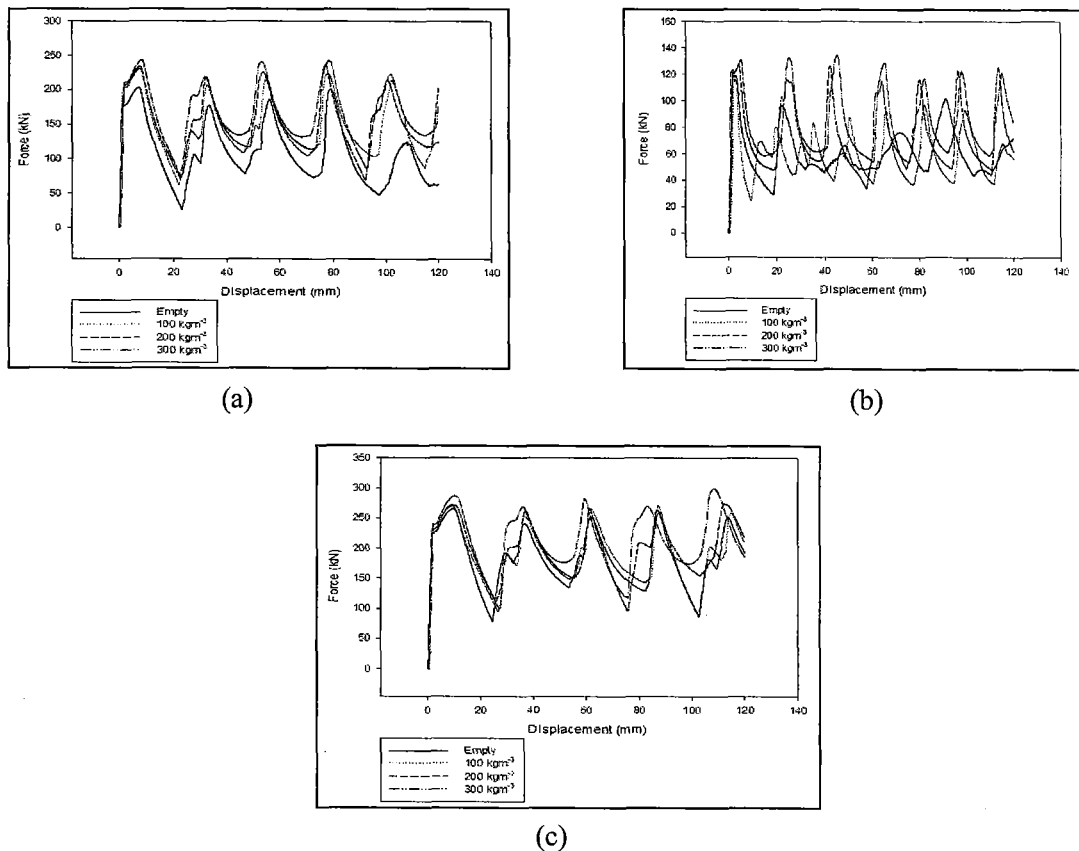


Fig. 1: Load-displacement curves for unfilled and filled foam tubes. (a) 1.9mm; (b) 2.9mm; (c) 3.6mm

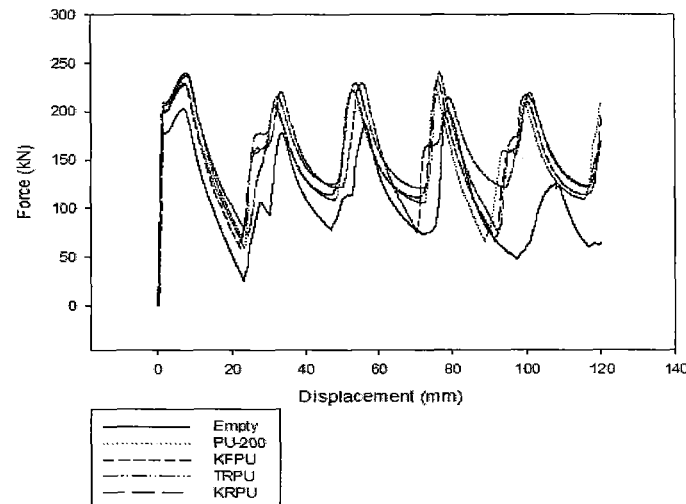


Fig. 2: Load-displacement curves of empty and composite PU foam-filled tubes at density  $200 \text{ kgm}^{-3}$  and tube thickness, 2.9mm

**Energy absorption.** The energy absorption ( $E$ ) of each tube is defined as the energy required to cause the collapse mode observed. Firstly, the energy is converted into elastic strain energy in the deform tube and the remainder is dissipated in plastic deformation during collapse. The energy absorption of the structures was evaluated by measuring the area under the force-displacement curves that generated during the quasi-static crush tests. The energy absorption of empty and PU composite foam-filled tubes is presented in Fig. 3a-3c. It is clearly indicated that energy absorption capacities of PU composite foam-filled tubes is higher than PU foam-filled tubes and empty tubes. TRPU foam-filled tubes show higher energy absorption value followed by KRPU, KFPU and PU foam-filled tubes at particular foam density.

For tube (T1), the energy absorption capacity improved by 23.2%, 22.4% and 12.7% according composite foam-filled tubes than PU foam-filled tubes, respectively at  $100 \text{ kgm}^{-3}$  density foam. For the same tube that filled with  $200 \text{ kgm}^{-3}$  density foam, the increment in energy absorption capacity was 13.1%, 11.2% and 7.1% according to the TRPU, KRPU and KFPU composite foam-filled tubes than PU foam-filled tubes, accordingly. Similarly, the energy absorption capacity improved by 8.8%, 6.2% and 4.9% for TRPU, KFPU and KRPU composite foam-filled tubes than PU foam-filled tubes respectively at  $300 \text{ kgm}^{-3}$  density foam. Interestingly, it was noticed that as the foam density increases, the percentage increase of energy absorption capabilities decreases according tube samples.

**Collapse modes.** Lu et al. and Al Galib et al. [4,5] postulated that circular tube tends to collapse in progressive deformation mode. The similar pattern was observed for all the samples that have been tested. Two principal deformation modes were noticed such as concertina (axisymmetric) and mixed mode for the tested tubes. When the empty tubes with smaller thickness (T1) were compressed to 60% from the 200 mm height, three lobes are formed that consisted of one lobe with concertina mode and followed by ovalization with two lobes. This type of collapse mode is categorized as mixed mode deformation pattern. As the thickness of the tubes were increased to T2, the collapse mode changes to concertina modes with 4 lobes or folding. The large tube thickness, T3 was also collapsed in concertina modes with 3 lobes. Interestingly, it was found that the foam filling methods encourage the mixed mode pattern change to concertina mode for tube T1 thick. From Fig.2a, it is noted that the energy absorption capacity of empty tube (T1) higher than the foam-filled tubes. This is because of the mixed mode deformation that induces asymmetry, which can encourage the global bending mode (Euler mode), which would strongly restrict the capacity for energy absorption. However, the axisymmetric mode of deformation guarantees a progressive collapse; in this sense, it is preferable even though the energy assessment is not favorable. Figure 4 shows some example of the progressive collapse of empty and foam-filled tubes.

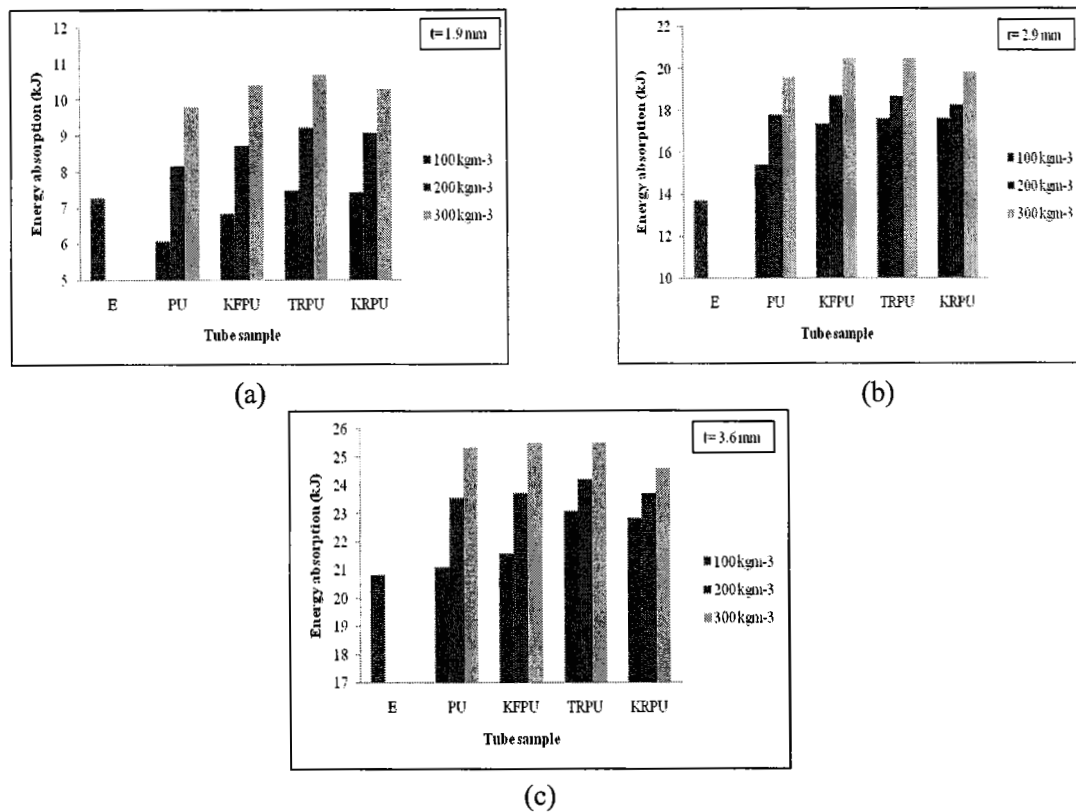


Fig. 3: Energy absorption values of composite foam-filled tubes at various densities. (a) T1; (b) T2; (c) T3

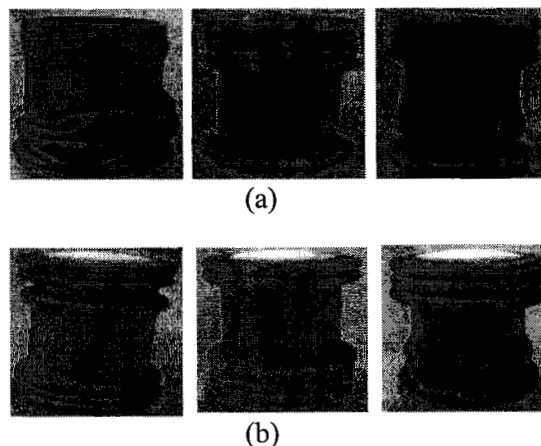


Fig. 4: The deformation modes of specimens: (a) Empty tubes, (b) foam-filled tubes

## Conclusions

An experimental investigation on energy absorption performance of polyurethane (PU) composite foam-filled tubes that subjected to quasi-static was presented in this paper. The quasi-static axial crushing investigation of these tubes suggested that the PU composite foam-filled tubes offer improved energy absorption capacity than PU foam-filled tubes. The results also indicated that the highest density foam exhibited highest energy absorption followed by intermediate density and lowest density. Furthermore, the energy absorption of tube enclosure is improved linearly with the

tube wall thickness. As the wall thicknesses increases, the energy absorption was increased. Interestingly, it was observed that the effect of foam density becomes insignificant when thick tubes are used. Overall, it was found that composite foam-filled tubes can be used as energy absorption device due to improved energy absorption capacity compared to other polymeric foam-filled tubes. Apart from that, the proposed device is an eco-friendly, sustainable and economical alternative component whilst offer better energy absorption characteristics.

### Acknowledgment

The author would like to acknowledge and thank polymer and ceramics laboratory, University Tun Hussien Onn Malaysia (UTHM), Everise Crimson (M) Sdn Bhd and Yong Fong Rubber Industries Sdn Bhd for material supply and support.

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10.4028/www.scientific.net/AMM.315

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10.4028/www.scientific.net/AMM.315.872